Self-phase modulation was measured by comparing output fundamental specra at low and high input powers. An Instrument Systems Spectro 320 scanned-grating spectrometer was used to measure pulse spectra. The resolution of the instrument is 0.3nm which is much smaller than the 6nm bandwidth of the fundamental pulses. Singlemode fibre optic inputs are used on the spectrometer, but this did not lead to any spurious phase modulation. Fig. 1 shows the output fundamental spectra at guided peak powers of 20W and 760W for a very small detuning from phasematch of 0.2nm. A characteristic SPM spectrum is seen for high power, with a narrowing of the central peak and growth of sidelobes. The low power spectrum is identical to the input spectrum. Numerical SPM modelling of short-pulse propagation in KTP [1] at this wavelength results in a peak nonlinear phase shift corresponding to this spectrum of 0.45π. The spectrum obtained numerically is shown in Fig. 2, where the frequency scale that results from the calculation has been scaled to wavelength through the measured bandwidth of the input spectrum. As can be seen, agreement between the theoretical spectrum and the experimental spectrum is very good. The asymmetry in the measured SPM spectrum is due to temporal walk-off and the detuning from phasematching. More symmetric spectra were seen at phasematching, but with reduced peak nonlinear phase shifts. In addition, SPM was only observed in the vicinity of the phasematch wavelength, thus indicating that it is caused by the cascaded second-order process rather than through $\chi^{(3)}$.

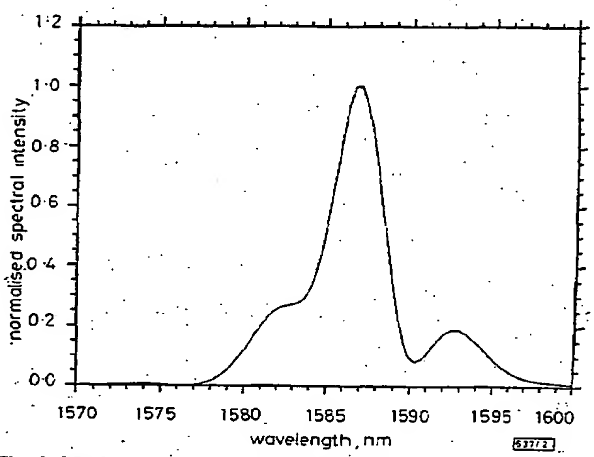

Fig. 2 *SPM spectrum obtained from numerical BPM for I = 1.5GW/cm^2, $\Delta kL = 0.02\pi$, $L = 1L_{w}$, λ = 1.587µm*

An effective nonlinear refractive index can be calculated from the measured nonlinear phase shift. Using the geometric area as an estimate of the waveguide effective area gives a guided fundamental intensity of 1.5GW/cm^2, which results in an effective n_2 = 6.8×10^{-14}cm^2/W for the 0.45π phase shift measured in this sample. This number is comparable to that of AlGaAs at 1.55µm, which has proven to be a promising material for all-optical switching in the telecommunications window [8]. Thus, cascading potentially offers a new means of performing switching operations at these wavelengths, and the wide availability of high quality, well characterised $\chi^{(2)}$ materials makes this approach especially promising.

23 June 1994
Electronics Letters Online No: 19940966

M. L. Sundheimer, A. Villeneuve and G. I. Stegeman (*CREOL, University of Central Florida, 12424 Research Parkway Orlando, FL 32826, USA*)

J. D. Bierlein (*E. I. Du Pont de Nemours & Co. Central Research & Development, Experimental Station PO Box 80356 Wilmington, DE 19880, USA*)

A. Villeneuve: Current address: COPL, Université Laval, Québec G1K 7P4, Canada

References

1 SUNDHEIMER, M.L., BOSSHARD, CH., VAN STRYLAND, E.W., STEGEMAN, G.I., and BIERLEIN, J.D.: 'Large nonlinear phase modulation in quasi-phase-matched KTP waveguides as a result of cascaded second-order processes', *Opt. Lett.*, 1993, **18**, pp. 1397–1399

2 THOMAS, J.-M.R., and TARAN, J.-P.E.: 'Pulse distortions in mismatched second harmonic generation', *Opt. Commun.*, 1972, **4**, pp. 329–334

3 DESALVO, R., HAGAN, D.J., SHEIK-BAHAE, M., STEGEMAN, G., VAN STRYLAND, E.W., and VANHERZEELE, H.: 'Self-focusing and self-defocusing by cascaded second-order effects in KTP', *Opt. Lett.*, 1992, **17**, pp. 28–30

4 STEGEMAN, G.I., SHEIK-BAHAE, M., VAN STRYLAND, E.W., and ASSANTO, G.: 'Large nonlinear phase shifts in second-order nonlinear-optical processes', *Opt. Lett.*, 1993, **18**, pp. 13–15

5 SCHIEK, R.: 'Nonlinear refraction caused by cascaded second-order nonlinearity in optical waveguide structures', *J. Opt. Soc. Am. B*, 1993, **10**, pp. 1848–1855

6 VAN DER POEL, C.J., BIERLEIN, J.D., BROWN, J.B., and COLAK, S.: 'Efficient type I blue second-harmonic generation in periodically segmented $KTiOPO_4$ waveguides', *Appl. Phys. Lett.*, 1990, **57**, pp. 2074–2076

7 BIERLEIN, J.D., and VANHERZEELE, H.: 'Potassium titanyl phosphate: properties and new applications', *J. Opt. Soc. Am. B*, 1989, **6**, pp. 622–633

8 AITCHISON, J.S., KEAN, A.H., IRONSIDE, C.N., VILLENEUVE, A., and STEGEMAN, G.I.: 'Ultrafast all-optical switching in $Al_{0.18}Ga_{0.82}As$ directional coupler in 1.55µm spectral region', *Electron. Lett.*, 1991, **27**, pp. 1709–1710

Direct UV writing of buried singlemode channel waveguides in Ge-doped silica films

M. Svalgaard, C.V. Poulsen, A. Bjarklev and O. Poulsen

Indexing terms: Optical waveguides, Chemical vapour deposition, Integrated optics, Photorefractive effect

Germanosilicate film waveguides fabricated by plasma enhanced chemical vapour deposition have been shown to possess high sensitivity towards UV induced index changes. As an illustration of possible future applications, direct point-to-point writing of buried singlemode channel waveguides using a focused, continuous wave, UV laser beam is demonstrated.

Introduction: In recent years much attention has been directed towards the process and applications of the UV induced refractive index change in germanosilicate glasses. The process of UV induced index change is complex and not yet fully understood [1, 2]. Until recently most of the work in this field has been performed on Ge-doped silica fibres with pulsed laser systems as UV sources. However, recent advances in thin film silica deposition techniques are making it possible to extend this work to include direct UV writing of index structures for use in thin film photonics devices. Direct writing can dramatically simplify the fabrication of thin film photonics devices, because several complicated processing steps including photolithography and reactive ion etching (RIE) may be bypassed. Singlemode channel waveguides have recently been UV patterned with a pulsed UV source using a mask to define the guiding structure [3]. In this Letter we present a demonstration of direct point-to-point writing of buried singlemode channel waveguides using a focused, continuous wave (CW), UV laser beam.

Experiment: The film waveguide was fabricated in a plasma enhanced chemical vapour deposition (PECVD) chamber by depositing first an SiO_2 buffer layer followed by an SiO_2-GeO_2 core layer and finally an SiO_2 cladding on a 4" silicon wafer. The buffer-core-cladding thicknesses were 6, 2.5 and 6µm with refractive indices at 633 nm n_1, n_2, n_3 = 1.459, 1.475, 1.459, respectively. Secondary ion mass spectroscopy revealed a uniform core layer Ge concentration equal to ~11 mol%. Trace amounts of aluminum

were also detected in the annealed sample, which may be due to contamination from the PECVD chamber walls.

Our UV source was a continuous wave intracavity frequency doubled Ar^+ laser (Innova 300 FreD) producing up to 300mW nearly polarised light at a wavelength of 244 nm. The beam is first expanded (× 10) and low intensity flanges cut off with an aperture. Finally, the beam was focused by a single lens onto the film waveguide which was mounted on DC X-Y translation stages. Before commencing writing, the distance between the focusing lens and the silicon wafer was carefully adjusted so that the waist of the focused beam coincided with the wafer surface at an angle of incidence of 90°. We can position the beam waist to within ± 10μm of the wafer surface, which is small in comparison with the focal depth of ~70μm of our f = 50mm lens. We calculated the focal plane $1/e^2$ beam diameter to be 5 ± 1μm. Although adequate for our demonstration, beam waist diameters as small as ~1μm may be achieved with diffraction limited optics. To write waveguides with larger diameters the wafer was simply moved slightly out of focus to a location where the UV beam had the desired diameter.

For evaluation, 1.55μm light was coupled into the waveguide with a singlemode fibre. The far field distribution of the exiting light was then displayed via a microscope objective on an IR camera.

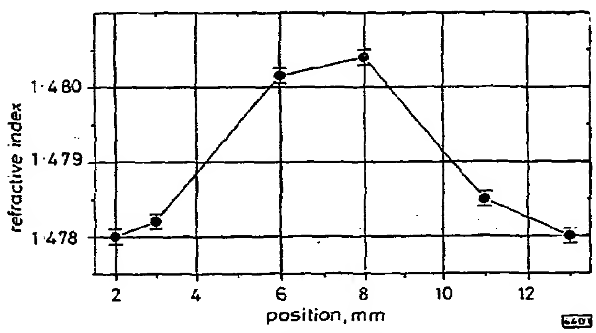

Fig. 1 *UV induced index change as measured with prism coupler setup*

Results and discussion: Before attempting to write channel waveguides we examined the degree of photosensitivity of the Ge doped layer. For this purpose a 3μm thick, single layer of SiO_2-GeO_2 was grown by PECVD and subsequently annealed for 2h at 800°C. With a prism coupler setup the refractive index of the film could be measured with a precision of 2×10^{-4}. After 45 min of 200mW UV exposure with a 2mm diameter beam we were able to measure an index change $\Delta n = 2.5 \times 10^{-3}$, as shown in Fig. 1 [4]. This index change is surprisingly large, because previously reported changes in non-photosensitised materials rarely exceed 10^{-3} [5]. Our result approaches that achieved in fibres photosensitised by hydrogen loading where index changes of the order of 10^{-2} have been reported [3]. We speculate that the high degree of photosensitivity in our samples may be due to the use of hydrogen (SiH_4 and GeH_4) in the PECVD process, increasing the density of Ge-Si wrong bonds. We also speculate that the photosensitivity in our samples may have been enhanced by the presence of trace amounts of aluminium, as has earlier been reported for fibres [5].

Encouraged by these results we proceeded with direct writing of buried channel waveguides. Linear structures with a length of 28mm and a separation of 300μm were written with different scanning speeds, v_{scan} = 20–500μm/s, and beam diameters, w_{beam} = 5–50μm. The UV power incident on the film waveguide was 70mW. Thus, a typical fluence of the order of 10^4J/cm², similar to that applied when writing gratings in fibres [5]. With UV beam diameters smaller than ~10μm, the structures could easily be seen visually on the film waveguide. Examples of typical singlemode profiles, measured horizontally (i.e. parallel to the film structure), are given in Fig. 2. Note that waveguides written in this experiment are elongated horizontally, because the thickness of the guiding layer is smaller than the UV beam width. The resulting elongation of the guiding mode is enhanced by the fact that the horizontal index step of the waveguide, induced by UV exposure, is smaller than the vertical index step. In some waveguides, written with large beam diameter and low scan speed, multimode characteristics in the horizontal distribution are observed.

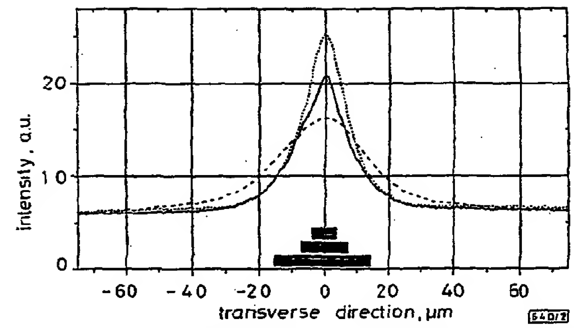

Fig. 2 *Typical mode profiles for w_{beam} = 7, 14, 30μm with v_{scan} = 100, 100, 50μm/s, respectively*

Bars illustrate the width of the laser beam
Laser beam diameter [μm]:

——— 1
- - - - - 14
- - - - 30

For waveguides written with beam diameters larger than ~15μm, the FWHM of the horizontal optical field (w_{mode}) increased with scanning speed. This behaviour is consistent with a nonsaturated situation where Δn increases with decreasing scanning speed. For smaller writing beam diameters, w_{mode} was nearly independent of the scanning speed. From simple theory it can be shown that w_{mode} becomes rather insensitive to further increases in the index step when the mode width approximately equals that of the guide. Therefore, it is difficult to determine whether we saturate the index change with smaller UV beam diameters. The measured optical field FWHM was compared to results from a simple effective index calculation suggesting index changes ranging from 10^{-4} to more than 10^{-3}, in good agreement with the initial prism coupler measurements.

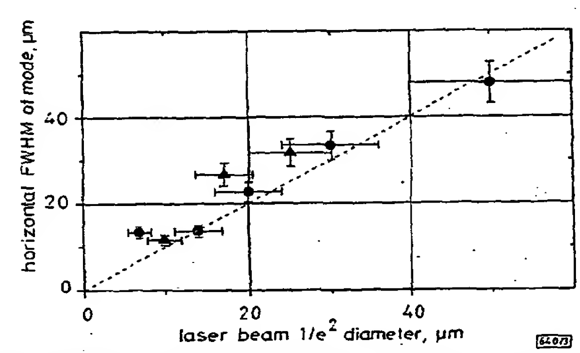

Fig. 3 *Minimum obtained FWHM of mode profile shown as function of corresponding UV beam diameter*

● first run
▲ second run

The minimal optical field FWHM is generally achieved with the smallest writing speed. Fig. 3 shows the minimum FWHM of the mode as a function of the writing beam diameter for two consecutive runs. It is evident that there is nearly a 1:1 relationship between the UV beam diameter and the mode width, demonstrating that we are able to control the mode width by varying the distance between the film waveguide and the focusing lens.

Conclusion: Germanosilicate thin films and thin film waveguides on silicon have been fabricated via PECVD. We have demonstrated a high degree of intrinsic photosensitivity, facilitating index changes of several times 10^{-3} for fluences of ~10^4J/cm² at 244 nm. With a focused continuous wave UV laser beam and DC X-Y translation stages we have demonstrated point-to-point writing of buried singlemode channel waveguides with diameters ranging from 5 to 50μm. Scanning speeds up to 500μm/s, limited by the apparatus, have yielded good results. Control of the guiding mode characteristics through the laser beam diameter and scanning

speed is achieved. Owing to the high intrinsic photosensitivity, no photosensitation prior to UV exposure is necessary to achieve these results. With submicrometre three-dimensional positioning and diffraction limited focusing of the UV beam, direct writing facilitates easy waveguide fabrication with high flexibility for novel devices.

 23 June 1994

Electronics Letters Online No: 19940935

M. Svalgaard, C. V. Poulsen and O. Poulsen (*Microelectronics Center, Bld. 345 East, Technical University of Denmark, DK-2800 Lyngby, Denmark*)

A. Bjarklev (*Electromagnetic Institute, Bld. 348, Technical University of Denmark, DK-2800 Lyngby, Denmark*)

References

1 DUVAL, Y., KASHYAP, R., and FLEMING, S.: 'Correlation between ultraviolet-induced refractive index change and photoluminescence in Ge-doped fiber', *Appl. Phys. Lett.*, 1992, 61, (25), pp. 2955–2957

2 MESH, M., SHLIFER, A., and TUR, M.: 'Observation of self-oscillating transmittance in germanosilicate optical fibres following long exposures at 514 nm', *Electron. Lett.*, 1994, 30, (1), pp. 77–78

3 MIZRAHI, V., LEMAIRE, P.J., ERDOGAN, T., REED, W.A., and DIGIOVANNI, D.J.: 'Ultraviolet laser fabrication of ultrastrong optical fiber gratings and of germania-doped channel waveguides', *Appl. Phys. Lett.*, 1993, 63, (13), pp. 1727–1729

4 POULSEN, C.V., SVALGAARD, M., and POULSEN, O.: 'Photosensitivity in germania doped silica films'. CLEO/EUROPE'94 CMM5, 1994,

5 MELTZ, G., and MOREY, W.W.: 'Bragg grating formation and germanosilicate fiber photosensitivity'. Proc. Int. Workshop on Photoinduced Self-Organization Effects in Optical Fiber, SPIE, 1991, Vol. 1516, pp. 185–199

Integrated optics for optical head applications

M. Ochiai, H. Temkin and R.F. Kazarinov

Indexing terms: Integrated optics, Optical storage

A waveguide structure for use in optical head systems is presented. The fabricated structures are $10 \times 2 \times 2mm^3$ and are <0.2g in mass. The waveguides propagate data and feedback signals for tracking and focusing. The proper generation of these signals and their sensitivity to the accompanying imaging optics are demonstrated.

Introduction: The access time of conventional optical recording or reading devices is limited primarily by the mass of the optical head. The optics consists of multiple miniature free space components, having tight optical and alignment tolerances, resulting in heads several centimetres in dimension and 50–100g in mass [1, 2]. Higher performance and improving laser technology require increasingly lighter and smaller optics, imposing even more stringent requirements on system design, fabrication, alignment and testing. Integrated optics technology offers both submicronmetre process control and planar fabrication, reducing head size, mass, and manufacturing costs. A fully integrated head using holographic lenses has been demonstrated [3], however, this system is currently limited by low grating efficiency and focusing power. Here, a hybrid approach is presented, in which waveguides are used to perform tracking and focusing functions, greatly reducing the number of discrete optical components required.

Device design: Fig. 1 shows a schematic diagram of the hybrid integrated optical head operation. The fundamental mode of a laser is launched into the centre waveguide. The light is then coupled to two adjacent subsidiary waveguides. The three waveguides terminate at different points along their respective axis, such that only the beam exiting from the centre waveguide is focused by a lens system on the disk surface. The two adjacent beams are focused slightly in front and to the back of the disk surface, respectively. Light reflected from the disk is collected by the lens and it propagates back through all three waveguides. The two subsidiary waveguides each branch into two separate waveguides. The reflected light intensities coupled out by the branch waveguides are detected and used to provide feedback signals used by the accompanying electronics to generate the appropriate servo-control signals.

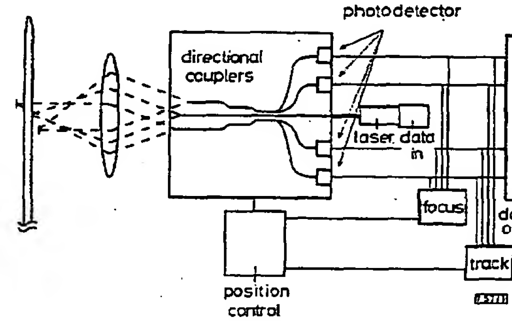

Fig. 1 *Schematic diagram of waveguided optical head operation*

When the centre beam is focused on the disk surface, light intensities reflected back through the two branch waveguides on either side of the centre waveguide are equal. However, if the disk 'wobbles', one of the adjacent beams is more tightly focused on the disk, and the resulting reflection signal will be stronger. An error signal generated by the comparison of the two detected signals is used to adjust the lens or waveguide structure to its proper focusing position along the optical axis. The two outside branch waveguides may be used in a similar manner.

Tracking of the centre beam in the plane of the disk is monitored by a signal generated by the reflected light emitted by the two adjacent branch waveguides on either side of the centre waveguide. When the centre beam is not centred on the track, the first order mode is reflected back in addition to the fundamental mode. The two modes interfere destructively and constructively in the two guides, respectively. Again, the differential intensities are used to initiate the appropriate adjustments.

Any combination of the four reflected light intensities may be used to generate the data signal. For polarisation sensitive systems, a polarisation splitter may be incorporated into the waveguide structure [4].

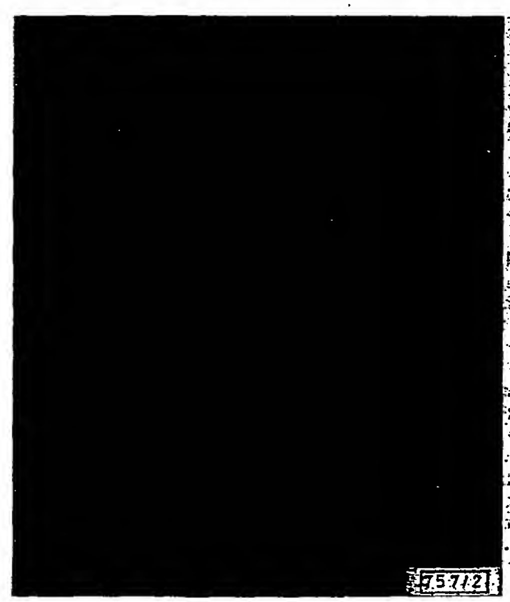

Fig. 2 *Photograph taken by an infrared camera showing the cross sectional view of the waveguide structure*

Direct writing of planar waveguide power splitters and directional couplers using a focused ultraviolet laser beam

M. Svalgaard

Indexing terms: Optical waveguides, Planar waveguides

Planar waveguide power splitters and directional couplers have been fabricated in silica using a continuous wave UV laser beam. The performance in terms of size, excess loss and spectral response is similar to that obtained with other techniques, while the fabrication time per device is a few minutes.

Introduction: Silica based planar waveguide devices are key components for high-speed signal processing in optical telecommunication networks. Hence, a great deal of effort is currently directed towards development of high volume production methods for such devices. The most common methods rely on photolithography and reactive ion etching for defining waveguide patterns in silica films fabricated using flame hydrolysis or chemical vapour deposition. An alternative method has recently been demonstrated where a focused continuous wave ultraviolet (UV) laser beam is used to directly write waveguides in germanosilica [1, 2]. This simple fabrication method requires less equipment and wafer processing and is therefore potentially cheaper and also more reliable than conventional techniques.

In this Letter, results are presented concerning direct UV writing of planar waveguide power splitters and directional couplers on a silicon substrate. The results indicate that the performance of these basic devices in terms of size, excess loss and spectral response is similar to that obtained with more complicated fabrication techniques relying on photolithography and reactive ion etching.

Experiment: Planar waveguides have been written into a photosensitive glass film using a focused 244nm continuous wave laser beam and high precision three dimensional translation stages [1, 2]. The sample consists of a 4 in silicon wafer with a three layer silica film waveguide fabricated by plasma enhanced chemical vapour deposition. The film waveguide core layer is 2.5μm thick and is co-doped with ~13mole% GeO_2. The wafer was cleaved into several pieces of length 33mm. The UV spot diameter on the sample is ~5μm and the incident UV power is 17mW. The sample was loaded prior to UV exposure with ~2mole% of deuterium to increase the photosensitivity [3]. After UV processing, the sample is annealed at 80°C to permit outdiffusion of residual deuterium and to increase the thermal stability of the UV induced index structures. Insertion loss measurements are performed by coupling light from a 1.54μm diode laser to the waveguides using standard singlemode fibres. The broadband spectral response may be evaluated on a spectrum analyser by replacing the diode laser with a white light source.

Results and discussion: Four port directional couplers and 1:2 power splitters have been fabricated using the direct UV writing technique. Such devices have been demonstrated previously [4, 5] using pulsed UV lasers and a metal mask defining the waveguide pattern; however these devices exhibited higher losses than normally obtained with standard techniques.

The power splitters presented here consist of a straight input arm splitting up into two straight output arms through symmetrical S-bends made with circular arcs. Straight and curved waveguides were written with different scan speeds to minimise the fabrication time while maintaining low loss, as previously reported [2]. From effective refractive index measurements using weak Bragg gratings [6] and comparison with numerical models [7], the UV induced refractive index change is estimated to be $\sim 3 \times 10^{-3}$ in the straight waveguides and $\sim 6 \times 10^{-3}$ in the bends. The splitters were fabricated in two steps, each including a scan of the input arm followed by the appropriate S-bend and output arm. Several splitters with an output arm separation of 200μm have been fabricated. The length of the region containing the splitter structure was varied from ~3 to ~8mm by varying the radius of curvature used in the S-bends from 30 to 170mm. Several straight reference waveguides were also fabricated along with the splitters.

The total insertion loss of the reference waveguides is ~3.7dB. This is mainly caused by coupling loss to the fibres, since the propagation loss is < 0.2dB/cm [2]. The excess splitter loss, defined as the ratio between the total transmitted power through a splitter and that through a reference waveguide, is typically < 0.2dB. Only for splitter lengths approaching 3mm did the loss increase above this value, most likely due to increased loss in the S-bends. Measurements of the spectral response from 0.9 to 1.65μm indicate a wavelength dependent splitting ratio for short device lengths. We speculate that this effect may be due to non-adiabatic field evolution in the splitting region. This behaviour is normally not desirable since it reduces the bandwidth of the device and prohibits symmetrical splitting from occurring at all but a few wavelengths. For splitters longer than approximately 6–7mm, the wavelength dependency is dramatically reduced. As shown in Fig. 1 for a 7.2mm long device, the splitting ratio is 50% within a few percent over a 400nm range from 1.25 to 1.65μm. For wavelengths < ~1.25μm, the splitting ratio is asymmetric, most probably due to a varying excitation of the multiple modes supported by the waveguides at these wavelengths.

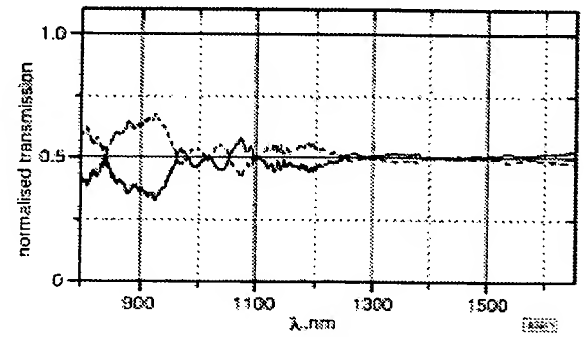

Fig. 1 *Spectral response of UV written power splitter*

Total length 7.2mm
detection arm 1
detection arm 2

The directional couplers presented in the following consist of dual waveguide input/output ports that are connected to a central coupling region by S-bends. The various sections of these couplers were written in a fashion similar to that described above. The length and centre-to-centre separation of the straight waveguides in the central coupling region are denoted L and c, respectively. A number of couplers have been fabricated with c = 9μm with L varying from 500 to 2600μm. The input/output port waveguide separation is 200μm, while the radius of curvature used in the S-bends is 40mm. The device length varies from approximately 8 to 10mm. Several straight waveguides, intended for calibration, were written along with the couplers.

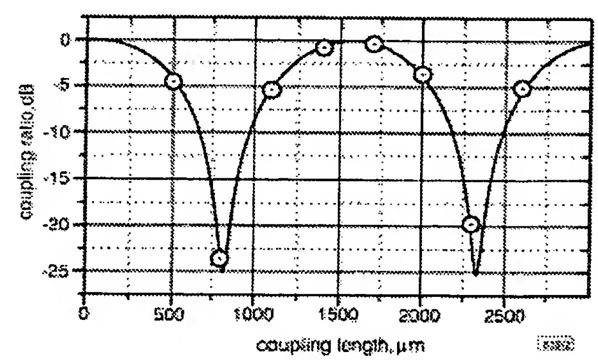

Fig. 2 *Coupling ratio against coupling length of UV written directional couplers*

⊙ measured
——— curve fit

The couplers were evaluated by exciting input arm 1 using the 1.54μm diode laser and measuring the coupling ratio, $P_1/(P_1 + P_2)$, where P_1 and P_2 is the power measured at output arm 1 and 2, respectively. The measurements are shown in Fig. 2 for varying L. All the couplers are symmetrical within the measurement accuracy, i.e. the observed coupling ratio does not change if input arm 2 is excited instead. The form of the coupling ratio expected from simple

coupled mode theory [8] has been fitted to the measured values with the coupling beat length, the amount of coupling occurring in the bends, and the maximum extinction ratio as free parameters and it is included in the Figure. In this way, a coupling beat length $L_c \simeq 760\mu m$ and a maximum extinction ratio of ~25dB is obtained. It may be shown [8] that such a high extinction ratio occurs when the propagation constant of each waveguide in the coupling region is identical within ~30ppm. The reproducibility of UV written waveguides is therefore quite high. The effective length describing coupling occurring in the bends is $\Delta L \simeq 695\mu m$, as obtained from the fit. This value, corresponding to nearly a full transfer of power in the bends, may be reduced by increasing the waveguide separation. The measured excess loss of the couplers is < 0.2dB for linear coupling regions up to ~1500µm in length, after which it increases to approximately 0.8dB. Higher loss for longer coupling lengths is to be expected since the supermode of the dual waveguide structure in the coupling region is more lossy and more affected by small imperfections in the host material than an isolated waveguide.

The fabrication time of the splitters and couplers described here has been approximately 13min per device. Recently, the amount of incident UV power has been increased, permitting higher scan velocities to be used. This has reduced the fabrication time to ~3min per device.

Conclusion: Direct writing in germanosilica with a focused UV laser beam has been used to fabricate power splitters and directional couplers. These devices exhibit low excess loss (<0.2dB) and good spectral characteristics while having a fabrication time of a few minutes. These results indicate that direct UV writing is a realistic alternative for high volume production of planar waveguide devices.

Acknowledgments: The author would like to thank C.V. Poulsen for fabricating the thin film sample and J.M. Jouanno for helpful comments.

4 August 1997
Electronics Letters Online No: 19971138

M. Svalgaard (*Microelectronics Center, Bldg. 345 east, Technical University of Denmark, DK-2800 Lyngby, Denmark*)

E-mail: svlgrd@mic.dtu.dk

References

1 SVALGAARD, M., POULSEN, C.V., BJARKLEV, A., and POULSEN, O.: 'Direct UV-writing of buried singlemode channel waveguides in Ge-doped silica films', *Electron. Lett.*, 1994, **30**, (17), pp. 1401–1402

2 SVALGAARD, M., and KRISTENSEN, M.: 'Directly UV written silica-on-silicon planar waveguides with low loss', *Electron. Lett.*, 1997, **33**, (10), pp. 861–863

3 LEMAIRE, P.J., ATKINS, R.M., MIZRAHI, V., and REED, W.A.: 'High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres', *Electron. Lett.*, 1993, **29**, (13), pp. 1191–1193

4 MAXWELL, G.D., and AINSLIE, B.J.: 'Demonstration of a directly written directional coupler using UV induced photosensitivity in a planar silica waveguide', *Electron. Lett.*, 1995, **31**, (2), pp. 95–96

5 HÜBNER, J., POULSEN, C.V., PEDERSEN, J.E., POULSEN, M.R., FEUCHTER, T., and KRISTENSEN, M.: 'UV-written Y-splitter in Ge-doped silica'. Conf. Lasers and Integrated Optoelectronics, (SPIE), 1996, Paper 2695A-11, pp. 98–105

6 POULSEN, C.V., HÜBNER, J., RASMUSSEN, T., ANDERSEN, L.-U.A., and KRISTENSEN, M.: 'Characterisation of dispersion properties in planar waveguides using UV induced Bragg gratings', *Electron. Lett.*, 1995, **31**, (17), pp. 1437–1438

7 SVALGAARD, M.: 'Ultraviolet light induced refractive index structures in germanosilica'. Ph.D. Thesis, Technical University of Denmark, 1997

8 SNYDER, A.W., and LOVE, J.D.: 'Optical waveguide theory' (Chapman & Hall, London 1983)